TESTS FOR FATIGUE STRENGTH AND BEHAVIOUR OF MATERIALS UNDER ALTERNATING STRESS

II. MULTI - STAGE REPETITION TESTS ~~TESTS~~ AND CHANGES IN THE PROPERTIES OF MATERIALS

M. Hempel

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(From German)

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Although fatigue tests conducted according to the Wöhler method are adequate for providing the basis for calculations for constructions which will be proof against fatigue fracture, the characteristics of materials under service conditions can only be demonstrated practically by multi-stage repetition tests. By investigation of the behaviour of materials during fatigue tests it was possible to discover the physical explanation of the fatigue values.*

WORKING STRENGTH AND MULTI-STAGE REPETITION TESTS

OPERATING CHARACTERISTICS AND WORKING STRENGTH TEST: For reasons of safety the design of many structural parts and components of machines and engines which have constantly to withstand high loads over long periods is determined so that the permissible stresses lie below the fatigue strength and form of the material chosen. Particularly in the construction of motors and motor vehicles, however, there are frequently critical speeds (resonance) during starting up or running and also under continuous operation which exceed the fatigue strength for shorter or longer periods. Components stressed in this way are subject to changing deflections of stress of varying magnitude and frequency; there is also an irregular alternation of periods of operation and rest, so that it is no longer possible to determine the fatigue strength by the Wöhler method. In this case it is necessary to determine the magnitude and time-behaviour of operating stresses by, for example, dynamic elongation measurements (1) ** over a fairly long loading period, taking into account the various conditions of stress; Figures 1 - 3 contain some examples illustrating the time-curve of working stresses which are neither periodic nor purely sinusoidal.

The testing of components ought to be conducted under the same conditions as in actual operation; but the commercial alternating stress testing machines do not permit any such tests. The following method has therefore been devised to make the test conditions equivalent to those of actual service: From the curves in Figs. 1 - 3 the stress-amplitudes are evaluated according to magnitude and frequency and curves obtained for the sums of the working loads (Fig. 4 - broken curve). The construction of the alternating-stress fatigue testing machines generally permits only a sinusoidal behaviour for the alternation of stress between constant stress limits. For this reason the sum-curve of working stresses must be divided into a step-shaped "sum-curve of test loads" by combining the individual

* Compare. M. Hempel: Tests for fatigue strength and behaviour of materials under alternating stress. Part I. Fatigue tests as a means of establishing bases for calculation. Z. VDI. 94 (1952) 809 - 15. (ACSIL TR. No. 677 - ACSIL/ADM/55/51).

** For references see end.

regions of stress-amplitudes (cf. Fig. 4). This produces a diagram representing the operating-strength test (2) - (7) as shown in Fig. 5. To make it easier to carry out such a test on the normal alternating-stress testing machines, these have in recent years been fitted, in many cases, with variable speed drives * and also with preset loading mechanisms. (8)

MULTI-STAGE TESTS

The difficulties to be faced in conducting and evaluating working strength tests are shown by the multiplicity of factors involved in multi-stage tests, e.g. the magnitude and duration of the overstress, the stages of loading, change of stress frequency, and rest periods,etc. Materials research is therefore directed towards gaining a basic knowledge of the effect of varying load sequences on changes in materials, e.g. hardening, damage, "training" **, etc. and determining the laws governing materials by single and multi-stage tests with increasing and diminishing loads in respect to time and resistance to alternating stress; from the results of these tests it will be possible to draw conclusions on the working behaviour of structural parts.

Figs. 6 - 14 contain some possible tests with one, two, or three stages, in which the mean stresses remain constant σ_m. The application of the Wöhler method, according to Figs. 6 - 8, is useful in obtaining the diagram of fatigue strength, for example, i.e. the fatigue strengths for various mean stresses. To obtain the damage-curve, i.e. the effect of overloading on fatigue strength, French's method of testing is applied (9), this is illustrated in Fig. 10. The test method for continuous "training" corresponds substantially to the case shown in Fig.12.

Figs. 15 - 22 show possible forms of load sequence in multi-stage repetition tests with constant or variable mean stress. With load changes between two stress limits, but with the same mean stress, the normal and overloads change, in one load sequence, after constant periods of time (Fig. 15) or after two (Fig. 16) or more different times (Fig. 17). Fig. 18 shows the case of a constant variation of alternating load between two limit values in one load sequence; Fig. 19 shows alternating loading with sudden overloading. Figs. 20 - 22 reproduce some test procedures involving load changes between different stress limits and with different mean stresses.

The procedures represented in Figs. 6 - 22 certainly make it possible, after taking into consideration the sequence of normal loading and overloading to make some pronouncement about the changes in fatigue strength or the damage, or rather the degree of damage, sustained; they give few indications, however, of the phenomena taking place in the material when subjected to these load conditions.

EXTENSION OF THE WÖHLER-GRAPH (DAMAGE CURVE)

Closely related to the multi-stage and working-strength tests are the tests which are made to determine the damage curve. The object of such tests is to obtain fundamentals for the design of components - such as springs, wire ropes, bracing wires, etc. for which it is not necessary to compute the unlimited fatigue strength because they are renewed after a definite time owing to the effect of wear, corrosion, or temperature. In this case calculations are made on the basis of time-strength, which is higher than fatigue strength, because the stress limits of the alternating stresses may exceed those of the fatigue strength in consequence of the

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* Variable speed testing machines designed by the Deutschen Versuchsanstalt für Luftfahrt were developed in conjunction with the Firm of C. Schenk. Darmstadt see DRP759264 (1940) (German Patents).

** "Training" indicates a process of prestressing below the fatigue limit whereby the material adapts itself so as better to withstand subsequent stresses.

limited duration of life. H.J. French (9) was the first to relate the change in breaking-load-cycles due to overloading to the fatigue strength and to introduce into the Wöhler-graph (Fig. 23) the boundary of a "probable zone of fatigue fracture risk". On the assumption that the damage curve b indicates the relation between the level of the stress and the time of the first incipient crack (i.e. the ultimate damage of the material), the behaviour of the curve b will depend to a great extent on the sensitivity of the procedure used to determine the first crack or the damage which has set in. The more sensitive the method, the further will the resulting damage curve b lie from the Wöhler-curve a (10) - (12). Previous investigations show that the most sensitive methods are those in which the decision about damage due to overloading rests on the determination whether the overstressed material still has the same fatigue strength as the material which has not been pre-stressed (French's procedure (9)).

In a Wöhler-graph the area between the Wöhler-curve and the two axes of co-ordinates may be divided into three zones in which at least two different processes are taking place in the material; in the first case, as a result of the constantly changing direction of deformation stress during the fatigue test, the increase in slip-resistance brings about a hardening effect; on the other hand, owing to a more active slip and thermal motion, distortion or loss of strength set in. It can be assumed also that both phenomena occur simultaneously and act in opposition; thus, according to the magnitude and duration of the load, either hardening or distortion may predominate. At present no information is available concerning the behaviour with time of this hardening-and-distortion function. One of the objectives of materials investigation must be test procedures in association with multi-stage tests for the determination of this function. Another pressing problem in connection with multi-stage tests is the explanation of the influence of frequency on time-strength, i.e. on the stresses which lie above the fatigue strength and which can be withstood for a limited time without damage.

BEHAVIOUR OF MATERIALS AND CHANGES IN PROPERTIES UNDER ALTERNATING STRESS

The evaluation and logical application of the results obtained from the preceding sections always presupposes a knowledge of the processes which take place in the materials under the imposed loading conditions. The tasks of this third group of investigations include, therefore, the discovery of the event during and after the formation of a crack leading to fatigue fracture and also the determination of the changes in properties during alternating loading.

PROPERTIES OF MATERIALS: Attempts to solve these problems included the experimental application of mechanical, electrical, magnetic, X-ray, metallographic, and analytical-chemical processes; also a theoretical application of the findings resulting from the study of plasticity and fracture phenomena.

The changes which occur in a material subjected to alternating stress have been ascertained many times by these procedures (13) - (15); it must be noticed that these investigations yield either a direct or an indirect indication of the changes; it is indirect chiefly in tests embracing changes in mechanical properties, such as the elastic limit, tensile strength, notch impact strength, and hardness; mention must also be made of changes in damping capacity and heat generation, also in the magnetic properties during alternation of stress.

The damping capacity (16), (17) is specially indicative of the onset of change in the material; it is more sensitive than the other properties just mentioned; the term is used to indicate the power of a material to convert into heat a part of the deformation work performed during stress alternation. At stresses below the fatigue strength the damping capacity reaches a stable limit as the duration of stress increases, above the fatigue strength it increases continuously until fatigue fracture occurs.

The changes with respect to time are specially dependent upon the nature and the condition of the material. Measurements indicate very clearly that in the volume of material under stress transformation of energy takes place and leads to heating of the material. In this connection mention should be made of the "shortening" tests of Stromeyer, Putnam-Harsch, Gough and Lehr (18), (19) for determining the fatigue strength from the temperature-load curves; a test bar was subjected to alternating stresses and the increases in temperature for the various load stages was measured after approximately $\frac{1}{2}$ to 2 minutes' time.

Figs. 24 and 25 give an indication of the time-relation of heat generation at different levels of alternating tension-compression stress until fracture occurs or until the fatigue tests end. It can be seen quite clearly from the temperature-time curves how the different zones of heat-generation shift in dependence upon the magnitude of the load. It should also be observed that with a frequency of 2000/min. without cooling of the specimens and also with loading at the higher time-strengths average temperatures of approximately 200 - 250°C may occur (cf. Fig. 25). The raising of the temperature of the bars into the zone of blue shortness is also the reason why, with this steel and under alternating stresses of $\pm$ 30 kg/mm^2 and $\pm$ 32 kg/mm^2 the pairs of values, alternating stress and fracture load-cycle, no longer be on the straight portion of the Wöhler curve. This is because the temperatures which occur lead to an increase in tensile strength and thus also in the fracture load-cycle (cf. Fig. 24). In the example reproduced the temperatures sometimes reach the range of re-crystallization, thus bringing about a change in the characteristics of the material which must be taken into consideration in any evaluation of its behaviour.

The use of mechanical, electrical or magnetic methods (20) give results which can be interpreted as predominantly the consequences of alternating stress; on the other hand microscopic (21 - 25) and X-ray (26 - 30) observations show that the cause of these changes is to be found in transformations of the structure and condition of individual crystals. Metallographic observations indicate that slip occurs under the constantly repeated deformation of alternating stress. Below a definite limit of deformation the formation of slip bands comes to an end after a small load cycle; above this limit the density of the slip bands increases. Moreover, recent research (24, 25) on cold-formed, subsequently fatigue-tested specimens of a mild steel with low C-content have shown that in a stress area somewhat above the fatigue strength spherical separations appear, like a string of pearls, in the slip bands (Figs. 26 - 30); by means of electro-chemical isolation and X-ray examination of the residue the nature of this separation was established as cementite (Fe_3C).

In the test cross-section (Fig. 26) the metallographic findings on the type and distribution of the separations are shown by shaded, etc., diagrammatic areas. The structure-photographs reproduced in Figs. 27 - 30 were obtained from the points 1-4 in the cross-section, located at the edge of the specimen, in the middle, and also at various distances from the fatigue fracture. It appears from the investigations that in the marginal zone of the specimen the separations are much more marked and more numerous than in the centre and that the quantity and distribution diminishes along the length of the test bar in correspondence with the increase in cross-section or the decrease in stress level. In the present example the test piece was elongated dynamically by 6% and then stressed somewhat above the fatigue strength $\sigma_W = \pm 25$ kg/mm^2 to breaking point ($N = 2.57 \cdot 10^6$ load cycles). As the elongation increases the separations become more marked and numerous, but fundamentally the same kind of distribution is maintained. One explanation of these observations rests on the fact that the surface crystals can flow more easily than those in the interior which are prevented from flowing by the adjacent crystals. It appears also that during the cold-forming process slip lines, or dislocations, are produced (31) and that the migration and concentration of carbon in these dislocations (diffusion) is facilitated by the supply of energy during the fatigue test.

It can also be expected that a deeper insight into the behaviour of a material subjected to alternating stress will be obtained by observations with X-rays (26 - 30) of the events in single crystals or individual crystallites of a polycrystalline material. If a coarse-crystalline material is used the X-ray photograph shows that the diffraction patterns are composed of single points which appear more or less sharp according to the degree of lattice distortions and crystallite deformations. From such experiments the remarkable finding emerged that fatigue strength is to be regarded as a deformation boundary (28 - 30). Where the stress was somewhat below or equal to the fatigue strength the deformation is confined substantially to single crystallites; above the fatigue strength the crystallite deformation is much more marked and observable in numerous crystallites (cf. also the following section).

In conclusion it must be pointed out that a deeper knowledge of the processes which take place during alternating stress can only be gained by the simultaneous application of several methods of investigation. Thus, for example, experiments on the effect of inclusions on fatigue strength must include the chemical and metallographic procedures (particularly electrochemical isolation (32)). The problem of the effect of heat-treatment of steels, especially of intermediate tempering, on the fatigue strength cannot be solved without a knowledge of the fundamentals determined by research on constitution (33, 34). The evaluation of long-period tests on heat-resisting steels at high temperatures under static or cyclic load to determine the changes which take place in their structure or crystals or study of their composition also requires the use of mechanical, chemical, metallographic and X-ray processes. Research on the properties of the marginal zones of test pieces (hardening, residual stresses, grain size, etc.) and their influence on the mechanical characteristics necessitates the use of surface testing instruments as well as metallographic and X-ray experimental methods (cf. sections "Fatigue Strength and Surface" and "Fatigue Strength and Temperature" in Note on p.1) In the analysis of fatigue tests, particularly the identification of deviations from the values for fatigue strength resulting from the manufacture, shape, and size of the specimens or other test circumstances, a statistical method of evaluating the results has been introduced in recent years (35 - 37).

THE MECHANISM OF FATIGUE FRACTURE: Theoretical treatment of the events in materials under alternating stress principally involves theories of the lattice and of energy, i.e. atomic processes. This often has for its point of departure two basic postulates. The first is that stress distribution is not homogeneous in a cross-section of a crystallite aggregation but undergoes great fluctuations from one crystal to another. According to the second, which is extensively confirmed by microscopic observation (cf. also the section "Properties of Materials"), the constant deformations resulting from alternating stress lead to slip in the crystals with transformation of energy.

The theoretical explanation of these phenomena is made more difficult because of the incompleteness of our knowledge of the behaviour of single crystals under alternating stress; the chief point which has still to be elucidated is whether the fatigue strength of single crystals coincides with their elastic limit (i.e. the stress at which noticeable flow can occur). In the case of polycrystalline materials there are, in addition to the flow and slip phenomena, elastic stress and distortion of the slip bands which govern the stress-hardening (31, 38). The hardening of a material which is often observed at the start of a fatigue test is caused by slip. Bound up with this slip-hardening there is, according to the amount and duration of stress, a diffusion process resulting from the back and forth movement of dislocations (dissipation) (38), (39).

The basic conception of slip and movement, or breaking up, of dislocations is not adequate, however, for the explanation of events with loads below and above the fatigue strength. Particularly in the case of loads above fatigue strength there is a lack of knowledge about the conditions leading to fracture or rather the appearance of the first crack. The impressions of various authors vary a great deal in their interpretation of crack formation and the fracture itself (also in connection with the occurrence of slip lines, crystal distortion or crystal dislocation); exhaustion of the capacity for deformation (40), exceeding a definite damping capacity (41), local overstraining at weak points (42) - (45), increases in stress within and between the crystals (46), local increases in temperature (22), (47), etc. These different explanations of the nature of fatigue failure are also the reason for there being no generally applicable theory of fatigue strength (38) - (40); (43) - (50). There is no difference of opinion regarding the extension of a crack once it has formed. The progress of the crack until fracture occurs rests upon the raising of stress in consequence of notch influence at the ends of the crack and on a steadily increasing weakness of the supporting cross-section, i.e. an increase in the specific loading of the remainder of the cross-section. It is not yet possible to make any statement as to which of the above-mentioned ideas about crack formation correspond to the facts, because there is, so far, insufficient definite and comprehensive experimental information about the influence of frequency, temperature, "training", damage, etc. on the fatigue strength.

In conclusion mention will be made of yet another interpretation of the mechanism of fatigue fracture, based on the X-ray examination of dynamically-stressed test bars by H. Möller and M. Hempel (30). At loads above the fatigue strength there occurs at once in single crystals which are unfavourably orientated - and later, as the period of stress increases, in the entire crystallite aggregation - a non-homogeneous deformation due to bending slip (characterized by blurring of the diffraction points). When the load is below the fatigue strength there is no blurring of the diffraction points or only a slight amount in single crystals. If the specimen is previously stressed below the fatigue limit, subsequent stressing above that limit produces considerably less blurring of the diffraction points than when the specimens are overstressed immediately; i.e. even in the case of stressing below the fatigue limit, it must be assumed that slip, or deformation beyond the elastic limit, is taking place in the crystals and that this is the explanation for the strengthening observed.

It appears from these observations that deformation below the fatigue strength is homogeneous, so that it consists of a purely sliding movement (without any twisting of the slip bands). The transition from slip to shear which can be recognized macroscopically by the shape of the diffraction points, corresponds to the point at which the fatigue limit is exceeded. The greater deformation involved leads to dislocation and distortion of quite large crystal-areas, in macroscopic measure, and cannot be endured for an indefinite time as is the case with the sub-microscopic homogeneous deformation of the crystal. In most cases cracks are developed along the planes of slip which show greatest deformation. This sub-microscopic crack-formation may be regarded as the beginning of the damage, i.e. disintegration. A further consequence of this crack-formation at numerous points in a crystallite aggregation (structure) is a complete change in stress-distribution, as a result of which points at which notch-stress is high appear next to points at which the stress is becoming weaker; thus all cracks will not necessarily become bigger as the duration of stress increases. Some, however, will develop and become visible as macroscopic cracks, of which one will finally produce a fatigue fracture.

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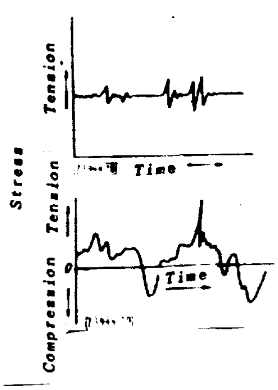
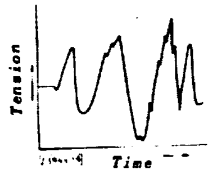




Figs.1-3: Behaviour of the working stresses with time. (Operating characteristics)

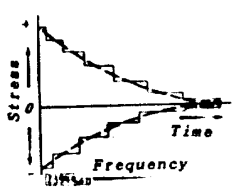


Fig.4: Sum-curve of operating stresses and step-shaped subdivision

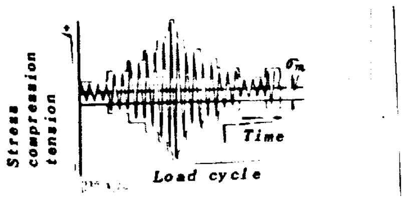


Fig.5: Diagram illustrating an operating strength test σ_m mean stress

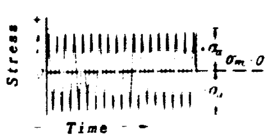


Fig.6: Test with $\sigma_m = 0$

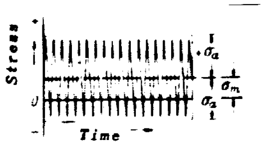


Fig.7: Test with $\sigma_m = \sigma_a$

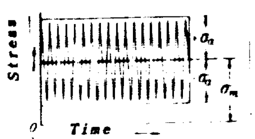


Fig.8: Test with $\sigma_m > \sigma_a$

Figs.6-8: Single stage test with constant mean stress σ_m and constant stress amplitude $\pm\ \sigma_a$.

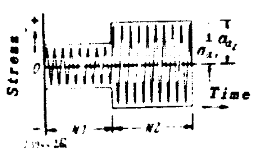


Fig.9: Test with $\sigma_{a_1} < \sigma_{a_2}$

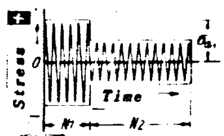


Fig.10: Test with $\sigma_{a_1} > \sigma_{a_2}$

Figs.9 and 10: Two stage test with constant mean stress σ_m

N_1 N_2 are the load cycles for the two stages σ_{a_1} and σ_{a_2} are the corresponding stress amplitudes.

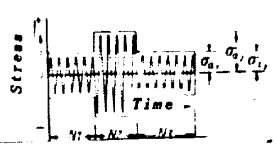


Fig.11: Test with $\sigma_{a_1} = \sigma_{a_3} < \sigma_{a_2}$

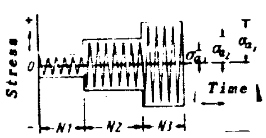


Fig.12: Test with $\sigma_{a_1} < \sigma_{a_2} < \sigma_{a_3}$

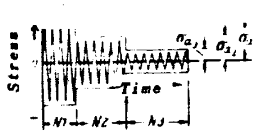


Fig.13: Test with $\sigma_{a_1} > \sigma_{a_2} > \sigma_{a_3}$

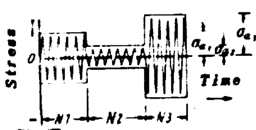


Fig.14: Test with $\sigma_{a_1} + \sigma_{a_2} \neq \sigma_{a_3}$

Figs. 11-14: Three stage test with constant mean stress σ_m.
N_1 to N_3 are the load cycles for the three stages.
σ_{a_1} to σ_{a_3} are the corresponding stress amplitudes.

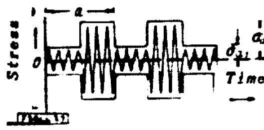


Fig.15: Load sequence of equal time intervals and $\sigma_{a_1} \neq \sigma_{a_2}$.

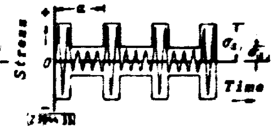


Fig.16: Load sequence with two different time intervals and $\sigma_{a_1} \neq \sigma_{a_2}$.

Fig.17: Load sequence with more than two different time intervals and $\sigma_{a_1} \neq \sigma_{a_2}$.

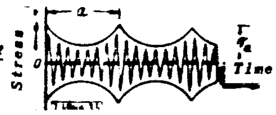


Fig 18: Load sequence with continuously varying amplitude of σ_a between an upper and a lower limit.

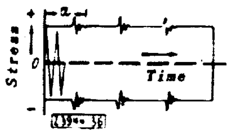


Fig.19: Load sequence with sudden overloading

Figs.15-19: Load sequence in multistage repetition tests with loading between two stress limits with equal mean stress.

Fig.20: Load sequence when $\sigma_{m_1} = \sigma_{m_2}, \sigma_{a_1} = \sigma_{a_2}$.

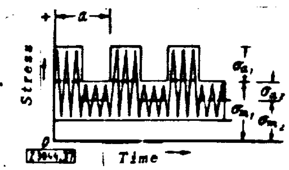


Fig.21: Load sequence with different stages throughout.

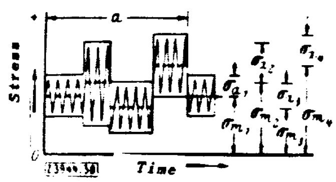
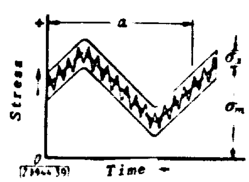


Fig.22: Load sequence with σ_a = const. σ_m continuously variable.



Figs.20-22: Load sequence in multistage repetition tests with loads between different stress limits with different stress limits with different mean stresses.

σ_a - one load sequence σ_a amplitude of stress indices
σ_m - mean stress   1, 2, 3 ... indicate the different stages.

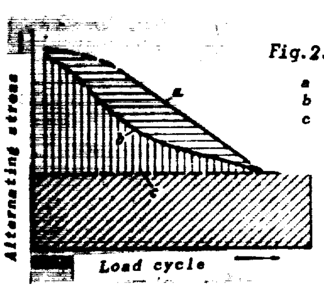


Fig.23: Extended Wöhler graph.

a - Wöhler-curve
b - damage curve
c - fatigue strength

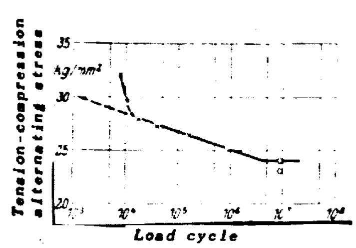


Fig.24: Behaviour of the Wöhler-curve in test bars under alternating stress.

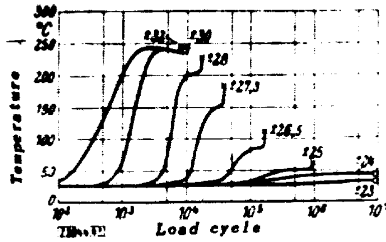


Fig.25: Generation of heat in specimens with Wöhler-curve as in Fig.24. Steel with 0.4%C: annealed 2 hours at 850°C in air: 0.2-limit $\sigma_{0,2}$ = 40 kg/mm²: tensile strength σ_B = 63.5 kg/mm²: test bars with 7.2 mm diameter and 15 mm cylindrical length without cooling - subjected to fatigue test: tension-compression alternating stress with frequency of 2000/min and mean stress σ_m = 0.

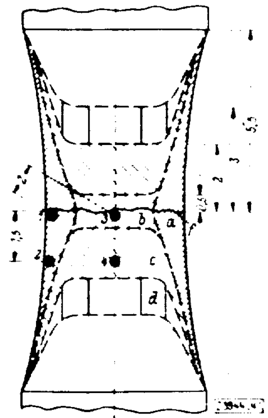


Fig.26: Test cross-section of a soft iron specimen with fatigue fracture, also marginal and centre zones after 6% dynamic cold-working and alternating stress.

The figures in the arrows give the measurement in mm and the points 1-4 give the places at which structure photographs were taken. The alternating load was $\sigma_w = \pm 25$ kg/mm², the fracture occurred after 2.57 . 10^6 load reversals. Zone a had very many, b many, c few, d very few, and e no separations. f - location of the fatigue fracture.

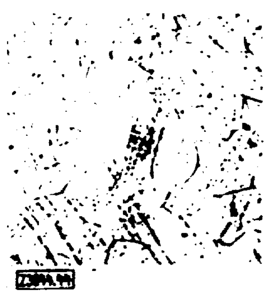


Fig.27: Photo of structure at Pt.1.

Fig.28: Photo of structure at Pt. 2.

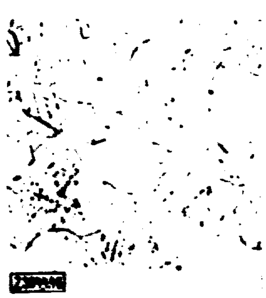


Fig.29: Photo of structure at Pt. 3.

Fig.30: Photo of structure at Pt. 4.

Figs.27 - 30: Structural changes in the specimen in Figure 26.